PLANT SCIENCE TODAY
Vol 12(3): 1-12
https://doi.org/10.14719/pst.8115

eISSN 2348-1900

REVIEW ARTICLE

Assessing the impact of climate change on forest biomass and carbon sequestration in India: A systematic review

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Received: 06 March 2025; Accepted: 06 June 2025; Available online: Version 1.0: 06 July 2025; Version 2.0: 14 July 2025

Cite this article: Suwethaasri D, Baranidharan K, Ravi R, Tilak M, Kalpana M, Ragunath KP, Hemalatha P, Vijayabhama M, Kabinesh V, Bargavi S, Krishnamoorthi S, Aiswaryalakshmi AR. Assessing the impact of climate change on forest biomass and carbon sequestration in India: A systematic review. Plant Science Today. 2025; 12(3): 1-12. https://doi.org/10.14719/pst.8115

Abstract

Forests are essential in combating climate change by functioning as carbon sinks, sequestering atmospheric carbon dioxide and storing it in biomass and soil. India, possessing various forest ecosystems, holds substantial potential for carbon sequestration. Climate change, marked by increasing temperatures, altered precipitation patterns and extreme weather phenomena, jeopardizes forest biomass and carbon sequestration. This systematic analysis evaluates the effects of climate change on forest biomass and carbon sequestration in several forest types in India. The study evaluates different methodologies for biomass estimation, including destructive, non-destructive and remote sensing approaches. It highlights the contributions of diverse forest types such as Himalayan forests, tropical rainforests, deciduous forests, mangroves and agroforestry systems in carbon sequestration. The findings indicate that while Indian forests act as vital carbon reservoirs, deforestation, land-use changes and climate-induced stressors have generally decreased the carbon sequestration potential of these forests by reducing biomass accumulation and increasing ecosystem stress, although variability exists across forest types. Sustainable forest management, afforestation and climate-resilient strategies are essential to enhance carbon storage. Integrating remote sensing technologies, ecological modeling and policy frameworks like REDD+ can aid in better monitoring and conservation efforts. This review provides insights into future strategies to strengthen India's forest carbon sequestration capacity and mitigate climate change impacts.

Keywords: carbon capture; carbon sequestration; climate change; forest biomass; forest management; Indian forests; storage

Introduction

Forests are among the most valuable assets in global efforts to control climate change due to their functions as carbon sinks, where CO_2 from the atmosphere is assimilated and held in biomass and soil (1). As a country whose forest ecosystems extend from the mountainous Himalayas to the rainforests near the equator, India poses immense carbon-sequestration opportunity. Nonetheless, climate change poses these ecosystems at risk by changing temperature regimes and precipitation patterns, raising the frequency of extreme weather conditions, which could affect forest biomass and carbon sequestration potential (2).

Carbon sequestration means capturing and depositing atmospheric CO_2 in biomass, soil and other long-term carbon pools. Indian forests, occupying about 21.71 % of the national geographical area, act as important sinks for carbon contributing to global climate regulation (3). Forest carbon is determined by forest type, age, species and environmental conditions. Although forests naturally have the capacity to sequester carbon, anthropogenic stress and climate change present major challenges to their effectiveness. It is important to know how various forest types in India help sequester carbon to formulate effective conservation and mitigation measures (4).

Himalayan forests: carbon storage in cold environments

Himalayan forests, which include coniferous and mixed temperate forests, are significant in sequestering carbon because of their immense biomass and slower decomposition rates. Carbon is sequestered in tree biomass, soil organic matter and litter in such forests (5). But increased temperatures, changing precipitation patterns and enhanced landslide and glacial melt events compromise their capacity for sequestering carbon. Land-use changes and deforestation further contribute to loss of carbon from such sensitive ecosystems. Conservation activities like afforestation, eco-friendly forestry management and ecosystem-based adaptation can contribute towards increasing carbon sequestration in the Himalayan region (6).

Tropical rainforests: the carbon sequestration powerhouses

Indian tropical rainforests, primarily located in the Western Ghats, northeast states and Andaman and Nicobar Islands, are some of the most carbon-sequestering productive ecosystems. These rainforests have high biomass accumulation because of high growth rates of trees and dense canopy cover (7). Deforestation, agricultural land conversion and climate change -driven rainfall pattern shifts threaten these forests severely. Climate variability may affect species composition and hence alter carbon dynamics. Conservation policies need to be reinforced, sustainable land-use practices encouraged and climate-resilient forestry incorporated to maintain their carbon sequestration potential (8).

Deciduous forests and potential carbon storage

Moist and dry deciduous forests cover a large area of India and hold a substantial carbon sequestration potential. Both have seasonal leaf fall, with major carbon contribution to the soil. Deciduous moist forests in central and southern India are richer in biomass and carbon stock than dry deciduous forests, which are more exposed to climate-related stressors like long-duration droughts and forest fires (9). Sustainable forest management, prescribed burning and assisted natural regeneration can improve the carbon sequestration in such forests.

Mangroves: blue carbon and coastal resilience

Mangrove forests, found along India's coast, especially in the Sundarbans, Godavari and Gujarat, are great carbon sinks as they can accumulate carbon in both biomass and waterlogged sediments. These have been called "blue carbon" ecosystems as they are vital for climate change mitigation through the protection of coasts from erosion, mitigation of storm surge effects and the sequestration of huge quantities of carbon (10). These are, however, threatened by rising sea levels, salinization and encroachments associated with human activities. Their carbon sequestration capability and climate change resilience can be improved through conservation efforts, mangrove afforestation and integrated coastal zone management (11). Mangrove ecosystems average between 6 and 8 Mg CO_2 equivalent per hectare annually, which is approximately 2 to 4 times higher than most terrestrial forests. Even more remarkably, mangroves can sequester four times more carbon than rainforests can pound for pound.

India's semi-arid and dry forests, located in Rajasthan, Gujarat and the Deccan Plateau, are highly challenged in carbon sequestration due to low rainfall, high temperatures and soil erosion. They possess lower biomass accumulation and carbon storage capacity compared to other forests (12). Desertification and water scarcity due to climate change also pose a threat to their sustainability. Plantation of drought-resistant tree species, soil conservation measures and restoration activities can enhance their carbon sequestration capacity (13).

Agroforestry and carbon sequestration in managed ecosystems

Agroforestry, the integration of trees with crops and livestock, presents an opportunity for enhancing carbon sequestration in India's managed landscapes. It provides a dual benefit of improving livelihoods while capturing atmospheric carbon (14). Different agroforestry systems, such as silvopasture, alley cropping and multistrata agroforestry, contribute to soil carbon enrichment and biomass accumulation. Climate-smart agroforestry practices, farmer incentives and policy support can further enhance carbon sequestration in these systems while ensuring sustainability (15, 16).

Carbon sequestration in plantation forests

Plantation forests, including commercial plantations of teak, eucalyptus, rubber and bamboo, serve as significant carbon sinks in India (17). These forests have a high potential for carbon sequestration due to their fast growth and high biomass accumulation. However, monoculture plantations often lack biodiversity and can lead to soil degradation and water depletion. Promoting mixed-species plantations, sustainable harvesting and incorporating native species can improve carbon storage efficiency while maintaining ecological balance. Poplar plantations lead with the highest carbon sequestration rate at 8 Mg C ha^{-1} yr^{-1}, followed by eucalyptus at 6 Mg C ha^{-1} yr^{-1}. Teak plantations sequester 2 Mg C ha^{-1} yr^{-1} while sal forests store only 1 Mg C ha^{-1} yr^{-1} Total long-term carbon storage in plantation forests ranges from 101 to 156 Mg C ha^{-1} Indian forests and plantations collectively removed at least 0.125 Gt of CO_2 from the atmosphere in 1995 (18).

Urban green spaces and carbon management

Urbanization poses a growing challenge to carbon sequestration, but urban green spaces, including parks, green belts and tree plantations, contribute to carbon storage and improve air quality (19, 20). Green infrastructure initiatives, such as urban afforestation, rooftop gardens and vertical forests, can help mitigate carbon emissions in cities. Integrating carbon sequestration strategies in urban planning and promoting community-based tree-planting programs can enhance the role of urban forests in climate mitigation (21).

Underrepresented ecosystems: alpine scrub and thorn forests

Alpine scrub ecosystems, found above 3000 m in Jammu & Kashmir, Ladakh and parts of Himachal Pradesh and Sikkim, host slow-growing shrubs and stunted trees. These regions, though low in biomass, have resilient below-ground carbon pools and contribute to soil organic carbon through litter deposition under extreme climatic conditions. Permafrost and seasonal snow cover influence microbial activity and carbon retention. Thorn forests, distributed in Rajasthan, Gujarat and parts of the Deccan Plateau, are composed of drought-resistant species like Acacia, Prosopis and Ziziphus. Although these forests exhibit low biomass productivity (30-50 t ha^{-1}), they sequester carbon steadily under arid stress and offer potential for restoration through dryland afforestation and silvopasture. Both ecosystems warrant further attention due to their unique climatic stressors and their role in maintaining regional ecological balance under climate variability (Table 1). This review systematically evaluates the impact of climate change on forest biomass and carbon sequestration across India's diverse forest types. The objectives of the review are fourfold: (i) to compare methodological approaches used in estimating forest biomass and carbon, including destructive sampling, non-destructive measurements and remote sensing techniques; (ii) to assess the carbon sequestration potential of specific forest types; (iii) to identify spatial and ecological patterns in

Table 1. Average biomass and carbon sequestration by forest type in India

Forest Type	Avg. Biomass (t ha^{-1})	Carbon Sequestration Rate (Mg C ha^{-1} yr^{-1})	Key Notes
Tropical Rainforest	180-250	6-8	High productivity and dense canopy
Moist Deciduous Forest	120-160	4-6	Rich soil carbon, moderate disturbance
Dry Deciduous Forest	60-100	2-4	Vulnerable to drought and fires
Himalayan Coniferous	90-150	2-3	Slow decomposition, cold-tolerant
Mangroves (Blue Carbon)	100-150	6-8 (CO_2 eq.)	High below-ground carbon, waterlogged soils
Plantation Forests	100-180	1-8 (species-dependent)	Poplar > Eucalyptus > Teak > Sal
Agroforestry Systems	50-120	2-6	High soil carbon from litter and crops
Urban Forests/Greenbelts	30-80	1-3	Variable depending on species and space

biomass distribution across different geographic regions; and (iv) to analyze how current findings align with policy instruments such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), the Clean Development Mechanism (CDM) and India's Nationally Determined Contributions (NDCs) under the Paris Agreement. By addressing these objectives, the review aims to provide a focused and integrative framework that supports evidence-based strategies for enhancing forest-based carbon mitigation under future climate scenarios.

Methodology

To systematically assess how climate change is affecting India's forest biomass and carbon sequestration, a comprehensive literature review was conducted. The review looked at sequestration pools, biomass/carbon stock, basal area and a variety of forest types across a few forest ecosystems across the country. "Web of Science, Google Scholar, ResearchGate, offline journals, book chapters, Indian government scientific reports, data from the Forest Survey of India (FSI), data from the Botanical Survey of India (BSI) and publications from the Indian Ministry of Environment, Forest and Climate Change were among the sources used in the January-August 2017 literature review. Only biomass and carbon sequestration in Indian forest ecosystems" were the subject of the study.

The methodology followed a structured approach

Keyword Generation: Keywords were developed to locate pertinent literature, encompassing terms such as biomass/ carbon stock, sequestration pool estimation, destructive and non-destructive methodologies, allometric equations "for biomass/carbon estimation and biomass status across various forest types in India (including plantation forests, natural forests, agroforestry and shrub biomass)."

Literature Search: A thorough literature search was performed across many online platforms (Google Scholar, Web of Science, journal databases), offline journals and book chapters from Indian forestry institutes. Moreover, government policies and reports were examined.

Data Collection and Analysis: The pertinent study findings were aggregated and examined, emphasizing significant observations about biomass and carbon stocks across various forest types, including tropical, temperate, alpine and coniferous forests, especially in the Himalayan area.

Cross-Referencing and Data Selection: Relevant research publications demonstrating connections (both positive and negative) between basal area and biomass, species diversity and species-specific biomass/carbon estimate were incorporated. Cross-references from chosen papers were included to guarantee thorough coverage.

In total, 150 critical research articles aligned with the study's objectives were identified and reviewed. Given the sporadic nature of research on Indian forest ecosystems, certain data gaps were noted and presented accordingly. The primary emphasis was placed on synthesizing existing knowledge rather than conducting new statistical analyses. However, key data from reviewed studies were presented where applicable. This systematic review serves as an updated resource on biomass and carbon sequestration in Indian forests, offering insights into the current state of knowledge in this domain (Table 2, Fig. 1). This visual representation shows the clustering and frequency of keywords used in the literature review on forest biomass and carbon sequestration in India. Keywords were generated using Boolean combinations and thematic mapping via (mention software if used, e.g., VOSviewer or NVivo). The figure illustrates the dominant research themes across forest types, sequestration methods and climate impacts.

Table 2. PRISMA summary table

Stage	Number of Records
Records identified (databases)	150
Additional sources	10
After duplicate removal	140
Records screened	140
Full-text articles reviewed	40
Studies included in synthesis	10
Records excluded	100
Articles excluded post-screening	30 (insufficient data, wrong outcome, design mismatch)

Results and Discussion

Methods for estimating biomass and carbon

In natural forest ecosystems, biomass accumulation plays a critical role in assessing productivity, sustainable utilization and atmospheric CO_2 sequestration (22). The accuracy of biomass estimation is crucial for various applications, including carbon cycle modeling, timber resource evaluation and carbon stock assessments. Several methods have been employed for estimating aboveground forest biomass and carbon storage, ranging from field-based measurements to remote sensing techniques (23).

Field-based methods can be categorized into destructive and non-destructive approaches. The destructive method, often referred to as the harvest method, involves felling trees and weighing individual components such as trunks, branches and leaves (24). While highly accurate, this

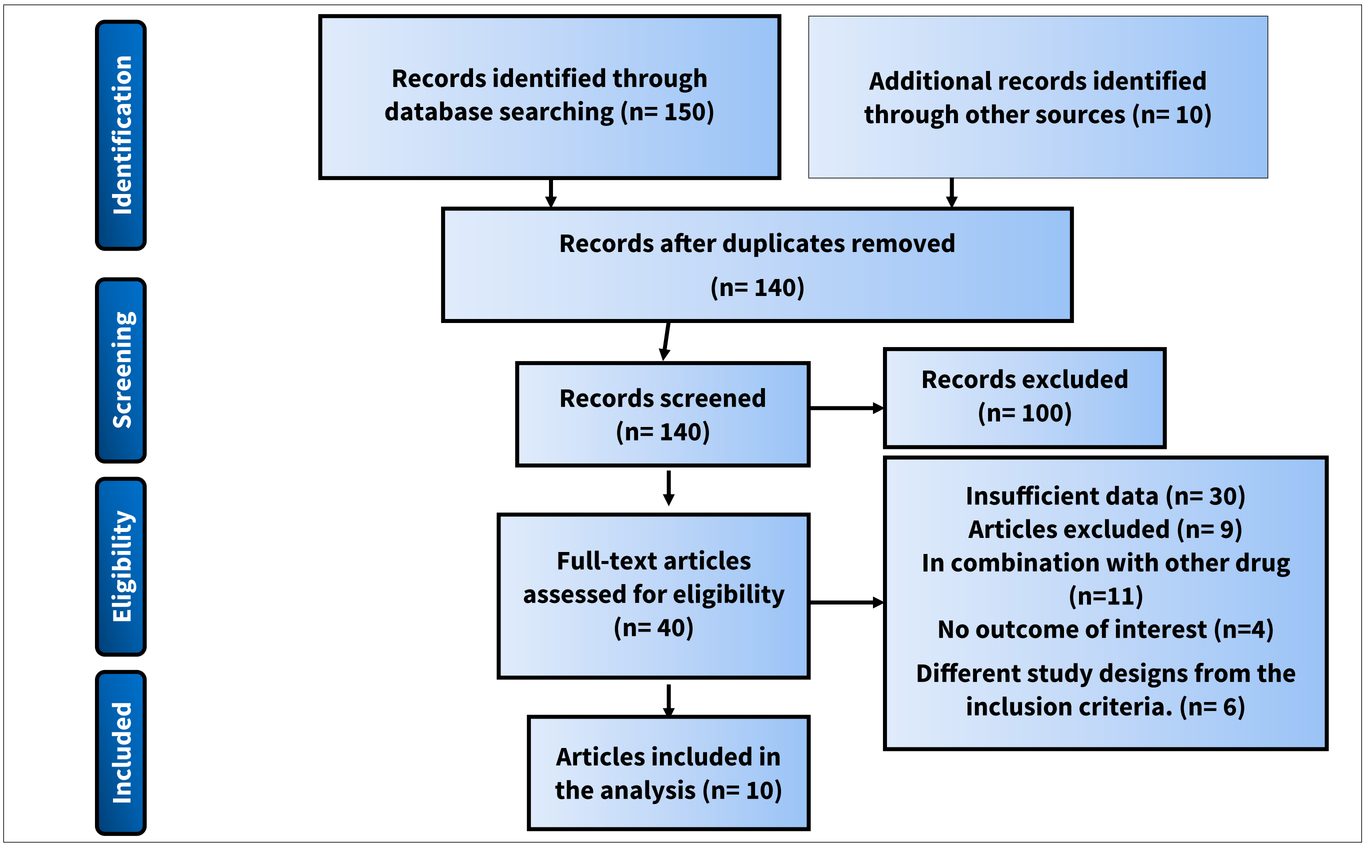

Fig. 1. Literature maps with keyword.

method is labor-intensive and impractical for large-scale studies, especially in degraded or protected forests. The non-destructive method, on the other hand, relies on measurable parameters such as tree height, basal area and wood density (25). Using allometric equations, biomass and carbon content can be estimated with reasonable accuracy. These equations, developed for specific species or mixed-species forests, provide a scalable alternative for large-area assessments (26).

Remote sensing and GIS-based techniques have gained prominence in recent years for estimating biomass and carbon stocks (27). Optical and radar-based satellite data, combined with ground-truth validation, offer a cost-effective way to monitor forest carbon dynamics over time (28). However, remote sensing methods still require field data calibration to improve accuracy and reliability.

Forest biomass and carbon sequestration in India

India's forests serve as a significant carbon reservoir, contributing to global carbon sequestration efforts. Several studies have attempted to quantify the biomass and carbon pool in Indian forests using different methodologies (29, 30). Historical estimates suggested that India's forest phytomass and carbon pool had undergone significant changes from 1880 to 1980 due to land-use modifications (31). Similarly, Dadhwal et al. (1998) (32), utilized FAO inventories to estimate phytomass carbon pools for 1980 and 1990, revealing variations across ecological zones.

India's total carbon stock was approximately 1085.06 Mt in 1984 and 1083.69 Mt in 1994, with the highest contributions from miscellaneous forests, *Shorea robusta* forests and *Tectona grandis* forests has been reported (33). A total forest biomass of 8683.7 Mt, where aboveground biomass accounted for 79 % and belowground biomass for 21 % has been estimated (34). The mean biomass density of Indian forests was calculated as 135.6 t ha^{-1}.

Further assessments indicate that Indian forests act as both carbon sinks and sources. A net carbon emission of 12.8 Tg C in 1994 has been estimated (35), whereas a carbon pool size ranging from 41 to 48 Mg C ha^{-1} between 1992 and 2002 has been reported (36). The fluctuations in India's forest biomass, with estimates decreasing from 3325 Mt in 2003 to 3161 Mt in 2007 has been observed (37). The net CO_2 fluxes were 372 Mt and 288 Mt for the first and second assessment periods, respectively (Table 3).

Species-specific contributions to carbon sequestration

Short-rotation plantation forests with regular leaf-shedding cycles exhibit higher carbon sequestration potential in litter (46). However, fast-growing conifers tend to produce slow-decomposing litter, negatively impacting soil productivity and increasing fire risk. Mixed plantations, incorporating both exotic and native species, have demonstrated higher efficiency in carbon sequestration compared to monoculture systems (47).

For afforestation and reforestation efforts, fast-growing species like *Eucalyptus* have been identified as ideal choices for wastelands, while softwood species are recommended for agrisilvicultural practices in plains (48). In rubber (*Hevea brasiliensis*) plantations, estimated an average carbon stock of 136 t C ha^{-1} in northeastern India, with soil contributing 92.7 t C ha^{-1} and additional sequestration occurring through litter fall and undergrowth vegetation (49).

Implications for climate change mitigation

The findings underscore the critical role of Indian forests in carbon sequestration and climate change mitigation (50).

Table 3. Estimates of phytomass carbon pool in forests based on different methodologies

Author	Forest Area (M ha)	Methodology	Phytomass Carbon Pool (Tg C)
Richards and Flint (1994) (38)	102.7/64.6	Historical records, ecological data and population-based forest biomass degradation model	7940/3426
Hingane (1991) (39)	52.6	Ecological studies-based mean phytomass density for two forest types	2587
Dadhwal et al. (1998) (32)	51.73	Using FAO inventories for ecological zone-wise five categories	3322/3117
Dadhwal (1982-1991) (40)	64.2/64.01	State-wise RS-based forest area, field inventories-based growing stock and crown density-based BEFs for two classes	3978/4071
Dadhwal (1993) (41)	64.2	Growing stock volume data and single conversion factor	1994
Salunkhe et al. (2018) (42)	64.01	RS-based area, crown cover fraction for 16 forest types, phytomass densities from ecological studies	4179
Chhabra et al. (2002) (34)	64.01	State-wise growing stock FSI data, BEFs as function of GSVD for three crown density classes, four forest categories	4341.8
Lal and Singh (2000) (43)	63.96	Forest stratum-wise growing stock volume FSI data and a standard BEF relating to wood volume by IPCC	2026

However, the variability in biomass estimation methods highlights the need for standardized approaches integrating field measurements, remote sensing and advanced modeling techniques (51). Sustainable forest management practices, afforestation initiatives and conservation strategies can enhance India's capacity to sequester carbon and mitigate climate change impacts effectively (Table 4).

Software and tools used for measuring

Measuring biomass and carbon involves a combination of field instruments, laboratory analysis and software tools for data acquisition, processing and modelling (62). Various instruments are commonly used, such as the CHN Analyzer (Elemental Analyzer), which measures carbon, hydrogen and nitrogen content in biomass samples and the Bomb Calorimeter, which determines the calorific value of biomass (63). Near-Infrared Spectroscopy (NIRS) is employed for assessing biomass composition and carbon content, while portable photosynthesis systems like the LI-COR LI-6400XT measure carbon exchange in plant biomass. Additionally, the dry weight measurement method, using oven drying, is a standard technique for determining total biomass weight (64).

For software-based biomass and carbon estimation, tools like WinRHIZO analyze root biomass from scanned images, while ImageJ is widely used for biomass quantification from images (65). Advanced remote sensing software such as ENVI and ERDAS IMAGINE process satellite imagery to assess vegetation biomass. Geographic Information System (GIS) tools like ArcGIS and QGIS enable spatial biomass and carbon mapping (66). Statistical computing platforms, including R (with packages like 'lidR' and 'biomass') and Python (using Pandas, SciPy, NumPy, Rasterio and GDAL), are extensively used for biomass modeling and analysis. Additionally, specialized software like CASS (Carbon Assessment Statistical Software) estimates carbon stocks from field data (67).

Remote sensing and modeling tools also play a crucial role in biomass and carbon assessment. MODIS (Moderate Resolution Imaging Spectroradiometer) provides satellite data for large-scale biomass estimation, while LIDAR (Light Detection and Ranging) measures forest structure and biomass through aerial surveys (68). DENDRO software is used in tree growth analysis for biomass estimation, whereas ecosystem modeling tools like BIOME-BGC and CENTURY simulate carbon and nutrient cycling in terrestrial environments (69). The Forest Vegetation Simulator (FVS) models forest growth and biomass accumulation, while CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector) quantifies carbon stocks in forest ecosystems (70). The integration of these instruments and software tools enhances accuracy in biomass and carbon estimation, facilitating environmental monitoring, ecological research and sustainable resource.

Assessment the impact of climate change

Assessing the impact of climate change requires a comprehensive analysis of ecological, socio-economic and atmospheric parameters. A significant study conducted by the Indian Institute of Science, Bangalore, examined the entire forest cover of India by analyzing 35190 forested grids

Table 4. Biomass estimates from different localities based on various studies

Locality	Aboveground Biomass (AG)	Belowground Biomass (BG)	Total Biomass	Source
Varanasi	–	7.6	–	Bandhu (1970) (51)
Varanasi	205.5	34.3	239.8	Singh (1975) (52)
Udaipur	28.2	–	–	Ranawat and Vyas (1975) (53)
Dehra Dun	129.6	–	–	Kaul et al. (1979) (54)
Varanasi	64.3	9.5	78.3	Singh (1981) (55)
Chandraprabha	95	–	–	Singh (1975) (52)
Tripura	114	24.4	138.6	Negi et al. (1990) (56)
Coimbatore	27.6	11.1	38.6	George et al. (1990) (57)
Haldwani	74.6–164.0	15.4–17.9	90.0–181.9	Negi et al. (1995) (58)
Chhindwara	28.1–85.3	9.1–15.6	37.1–100.9	Pande (2005) (59)
Madhya Pradesh (Dry Deciduous)	54.9	–	–	Salunkhe et al. (2017) (60)
Madhya Pradesh (Mixed Deciduous)	44.5	–	–	Salunkhe et al. (2014) (61)

(71). The findings revealed that more than two-thirds of these grids are expected to undergo vegetation changes by the year 2100, with nearly all major forest types being affected by projected climate shifts. These changes may have severe consequences, as different species exhibit varied responses to climate change (72). Some endemic species may experience a sharp decline in population and face the risk of extinction. Furthermore, these ecological disruptions are likely to have adverse socio-economic implications, particularly for forest-dependent communities and the broader economy. The study also emphasized that the impacts on forest ecosystems may be long-term and, in some cases, irreversible (73). However, one positive outcome is the projected increase in net primary productivity, particularly for tropical evergreen forests, which could rise by 1.5 times. In contrast, the rate of increase is expected to be lower for temperate deciduous, cool conifer and cold mixed forests (74).

Another study assessed the potential impacts of climate change on Indian forests for two future timeframes: 2021-2050 and 2071-2100. By 2035, when atmospheric CO_2 levels are expected to reach 490 ppm, approximately 30.6 % of the forested grids are projected to experience vegetation changes. By 2085, with CO_2 concentrations rising to 680 ppm, this figure is expected to rise to 45.9 % (75). The vulnerability assessment highlighted that at-risk forested grids are distributed across the country, with a higher concentration in the upper Himalayan stretches, parts of Central India, the Northern Western Ghats and the Eastern Ghats. In contrast, forests in Northeast India, the Southern Western Ghats and Eastern India are expected to be less vulnerable to climate change. The study further revealed that factors such as low tree density, reduced biodiversity and high levels of forest fragmentation contribute significantly to forest vulnerability (76). These findings underscore the urgency of continuous monitoring and adaptive management strategies to mitigate climate change impacts on forests. Utilizing remote sensing, ecological modeling and long-term field studies can help policymakers develop effective conservation and climate resilience strategies.

Advanced techniques and management strategies

Land managers play a crucial role in enhancing soil carbon sequestration through strategic interventions. These involve increasing organic matter input rates, directing carbon toward more stable carbon pools and prolonging the lifespan of these pools (77). Implementing sustainable agricultural practices can reverse the historical depletion of soil carbon stocks caused by intensive land use. Extensive research on soil management has provided valuable insights into processes that augment soil carbon content (78).

Cropping intensification

Cropping intensification strategies, such as eliminating fallow periods, utilizing high-yielding crop varieties and applying fertilizers and soil amendments, significantly boost organic matter production and soil carbon inputs (79). Precision agriculture further enhances soil carbon sequestration by optimizing resource use. However, while some crop residues decompose quickly and fail to contribute to long-term soil carbon storage, others undergo humification, promoting stable organic carbon accumulation. The effectiveness of cropping intensification in carbon sequestration is further enhanced when combined with organic amendments like manure and biologically altered inputs, which introduce resistant organic materials, fostering long-term soil organic carbon buildup. Tree species play crucial roles in cropping intensification strategies through agroforestry systems that enhance carbon sequestration while maintaining agricultural productivity. Fast-growing species like poplar achieve the highest net annual carbon sequestration rates at 8 Mg C ha^{-1} yr^{-1}, followed by eucalyptus at 6 Mg C ha^{-1} yr^{-1}, making them ideal for alley cropping systems where they are planted in rows between agricultural crops. *Leucaena leucocephala* serves as an excellent nitrogen-fixing tree in silvopastoral systems, enhancing soil fertility while sequestering carbon and when intercropped with teak, it increases tree growth and modifies soil characteristics positively. Major agroforestry tree species studied include eucalyptus, malabar neem, sandalwood, red sanders, teak and subabul, with combinations like malabar neem + sandalwood and red sanders + sandalwood showing enhanced carbon sequestration potential Moderate-growing species like teak sequester 2 Mg C ha^{-1} yr^{-1}, while long-rotation species like sal forests, though slower at 1 Mg C ha^{-1} yr^{-1}, store the largest carbon stock in living biomass at 82 Mg C ha^{-1} demonstrating how different tree species can be strategically integrated into intensive cropping systems to optimize both agricultural yields and carbon storage through their varying growth rates, nitrogen-fixing capabilities and biomass production patterns (80).

Conservation tillage

The conversion of native vegetation to row cropping often results in soil organic carbon (SOC) depletion due to mechanical soil disturbances. Soil structure plays a vital role in preserving organic matter by controlling microbial access and regulating decomposition rates. Soil aggregates serve as protective environments for labile organic matter, with macro aggregates (≥0.25 mm) being more vulnerable to disturbance than micro aggregates (<0.25 mm), which exhibit greater stability and slower turnover rates (81). Conservation tillage techniques, such as no-till farming and the establishment of perennial vegetation, minimize soil disturbance, allowing for the restoration of aggregation processes that enhance SOC storage (82). These practices also promote fungal-dominated organic matter cycling pathways, prolonging microbial residue retention in soil and increasing mycorrhizal fungal biomass. Furthermore, conservation tillage reduces erosion, which mitigates the loss of particulate organic matter and helps maintain soil fertility, water-holding capacity and overall crop productivity.

Liming, irrigation and fertilizer management

Soil amendments such as liming agents, fertilizers and irrigation adjustments significantly influence carbon sequestration. Transformations involving the formation of melanin-like humic compounds enhance the biochemical resistance of organic matter to decomposition. Phenoloxidase enzymes and abiotic oxidants facilitate these transformations, with studies suggesting that maintaining neutral or higher soil pH conditions improves enzyme stability and accelerates humic compound formation (82). Wetting-drying cycles and the presence of iron and manganese oxides further promote oxidative polymerization reactions, stabilizing soil carbon. Additionally, the sorption of organic compounds onto clay surfaces, facilitated by polyvalent cation bridges, protects against microbial degradation. Strategies such as managing drainage conditions and introducing divalent liming agents can enhance the sequestration of soil organic carbon by optimizing soil geochemical interactions (83).

Perennial vegetation

Establishing perennial vegetation on previously cultivated cropland can significantly increase soil carbon levels. This increase is driven by improved soil aggregation, a shift toward fungal-dominated decomposition pathways, enhanced organic matter inputs (particularly through roots and mycorrhizal fungi) and reduced soil erosion (84). Perennial vegetation also contributes to biomass accumulation, which plays a crucial role in carbon sequestration. In forest ecosystems, carbon sequestration in biomass often exceeds that in soil, but potential biomass losses due to fires or pest outbreaks must be considered in carbon balance assessments. Additionally, perennial biomass crops can offset fossil fuel usage, contributing to a continuous reduction in atmospheric carbon emissions (85). Unlike soil carbon accumulation, which reaches saturation over time, biofuel production from perennial crops offers an ongoing carbon offset potential.

Microbial manipulation

Soil microbial communities regulate organic matter decomposition and stabilization, making them key players in carbon sequestration. Advanced nucleic acid-based methods, including 16S and 18S ribosomal DNA probes and terminal restriction fragment length polymorphism (T-RFLP), allow for detailed profiling of microbial community structures in different land-use systems (86). Despite variations in microbial composition, fungal biomass typically increases under restored prairie conditions. Emerging technologies like DNA microarrays provide further insights into microbial community functions related to carbon sequestration. By leveraging these tools, researchers and land managers can manipulate microbial populations through strategies such as targeted inoculation, substrate amendments, or pH adjustments (87). These interventions can promote the formation of biochemically resistant compounds and enhance soil carbon stabilization processes.

Advantages of carbon capture and storage (CCS) or carbon sequestration (CS)

CCS can reduce emissions at the source

Nearly 50 % of greenhouse gas emissions in the United States originate from energy production and industrial activities. CCS technology has the potential to capture CO_2 directly from these point sources and store it permanently in geological formations (88). According to the International Energy Agency, CCS could mitigate up to 20 % of total CO_2 emissions from industrial and energy sectors.

CO_2 is less difficult to capture at point sources

CO_2 capture technologies are hindered by the low concentration of CO_2 in the atmosphere. On the other hand, CCS technologies like pre-combustion and oxyfuel combustion improve the efficiency of CO_2 capture by concentrating it in flue gases (89). These processes allow for more efficient CO_2 separation and storage using sorbent-based reactions.

Other pollutants can be captured concurrently

CCS technologies, especially oxyfuel combustion, lower nitrogen oxides (NOx) and sulfur dioxide (SO_2) emissions substantially (90). Argonne National Laboratory studies show that oxyfuel combustion can lower NOx emissions by as much as 50 % from traditional combustion. Electrostatic precipitators also have the capability to remove particulate matter produced during oxyfuel combustion, further enhancing air quality (91).

CCS may lower the social cost of carbon

The social cost of carbon refers to the economic damage caused by climate change because of CO_2 emissions. Through its capture and sequestration, CCS can help mitigate climate damage in the forms of extreme events and negative impacts on health and, at the same time, increase agricultural output (91). The emission reduction of CO_2 using CCS technology is thus an affordable policy for minimizing long-term environmental and economic hazards.

Through the integration of cutting-edge methods like cropping intensification, conservation tillage, soil amendment optimization, perennial crops and microbial manipulation, together with innovative carbon capture technologies, agriculture can become a critical agent in boosting global carbon sequestration processes (92). Such processes not only enhance the health and productivity of soils but also play a crucial role in the mitigation of climate change and environmental sustainability.

Uncertainties and limitations

Understanding the impact of climate change on forest carbon sequestration is constrained by several uncertainties:

- **Methodological Uncertainties** Variation in the application of allometric equations, lack of standardization in field measurements and differences in biomass expansion factors (BEFs) lead to inconsistent results across studies.
- **Remote Sensing Limitations** Challenges include cloud cover interference, terrain correction issues in mountainous regions and limited ground-truthing in remote ecosystems.
- **Climate Model Uncertainty** Regional projections often differ across General Circulation Models (GCMs), making it difficult to assign definitive climate stress responses to specific forest types.
- **Spatial Resolution and Scale** Biomass and carbon stock estimates are often extrapolated from limited sample plots, causing high variability when applied at state or national levels.
- **Data Gaps in Ecosystems** Alpine scrubs, thorn forests and degraded lands are underrepresented in biomass studies, which skews regional carbon budgets.
- **Socioeconomic and Policy Gaps** Forest-dependent community dynamics and land tenure systems are rarely factored into biomass models, limiting the practical

implementation of results.

Addressing these uncertainties requires the integration of multi-scale models, improved remote sensing calibration and investment in long-term ecological monitoring.

Challenges

Assessing the impact of climate change on forest biomass and carbon sequestration in India presents several challenges. One of the primary issues is the availability and quality of data. Long-term, high-resolution datasets on forest biomass and carbon stock changes are limited and the inconsistency in methodologies used across different studies makes comparability difficult. Additionally, remote sensing techniques, while valuable, face limitations due to cloud cover, terrain complexity and resolution constraints, making accurate biomass estimation a challenge. Field-based measurements, such as allometric equations and plot-based surveys, are often labor-intensive, time-consuming and geographically restricted. Integrating remote sensing with ground data for more reliable assessments remains a significant technical hurdle.

The other significant challenge is the uncertainties in climate models and projections. Future climate variables such as temperature, precipitation and extreme weather patterns are difficult to predict at localized scales and this creates challenges in determining clear associations between climate stressors and forest growth, biomass accumulation and carbon sequestration potential. Moreover, India's varied forest ecosystems ranging from tropical rainforests to temperate and mangrove forests vary in their response to climate stress and hence generalization is difficult. Regional variability of species, rates of growth and recovery in biomass and carbon storage complicates the climate change impact estimate further.

Anthropogenic pressures and land-use changes provide an additional dimension of complexity. Deforestation, urbanization and agricultural encroachment continue to decrease forest cover directly impacting the carbon sequestration capacity of forests. Overgrazing, illegal logging and fires contribute to degradation, making the long-term sustainability of forests as carbon sinks more challenging to evaluate. In addition, carbon accounting and policy framework shortfalls limit accurate evaluation and effective mitigation. Varying methodologies like the ones stated within the IPCC guidelines and the country inventories sometimes provide differing estimates of sequestration. Introducing forest carbon sequestration into mechanisms involving carbon credits remains a problem attributed to gaps within policy and execution.

Extreme climate events also pose other threats because more frequent instances of heatwaves, droughts and storms result in forest death as well as biomass loss, which have an impact on long-term carbon storage. Forest recovery after disturbance cannot be forecasted and this further makes predictions challenging. Soil carbon sequestration processes also rely on land-use history, microbial activity and climate variability, making the calculation of below-ground biomass contributions to overall carbon sequestration challenging. Finally, socioeconomic and institutional constraints are the key to assessment challenges. Frequently, there is a trade-off between conservation goals and the livelihood requirements of forest-dependent communities. Insufficient funds, technical skills and bureaucratic obstacles also hinder large-scale monitoring and the use of effective climate adaptation measures in the forestry sector. Solving these challenges involves a multi-dimensional strategy that combines cutting-edge technologies, policy measures and community involvement to achieve a better understanding of climate change effects on India's forests.

Future prospects

Despite the challenges, significant advancements in technology, research and policy efforts provide promising prospects for improving carbon sequestration and mitigating the impacts of climate change on Indian forests. The synergistic combination of remote sensing technologies such as LiDAR, hyperspectral photography and machine learning algorithms will yield more precise estimations of biomass and carbon stock. The development of region-specific allometric equations and improved ground-truthing methods would further boost carbon sequestration estimates. Afforestation and reforestation initiatives, such as India's Green India Mission and the Bonn Challenge, can substantially influence carbon sequestration. Enhancements in agroforestry and sustainable forest management would not only augment carbon sequestration but also improve biodiversity and ecosystem resilience. Climate-resilient trees, genetic enhancement through genetic engineering and aided migration initiatives will facilitate forest adaptation to fluctuating climate patterns and augment carbon sequestration capacity.

Policy frameworks and carbon market mechanisms must be strengthened to provide economic incentives for forest conservation. Promoting carbon trading via initiatives like REDD+ (Reducing Emissions from Deforestation and Forest Degradation) might facilitate the mobilization of international funding for forest protection, but this approach is significantly enhanced by complementary government initiatives. Article 6 of the Paris Agreement allows countries to voluntarily cooperate with each other to achieve emission reduction targets set out in their NDCs, enabling countries to transfer carbon credits earned from GHG emissions reduction, creating bilateral and multilateral carbon trading opportunities beyond REDD+. The Article 6.4 Mechanism serves as a new central crediting mechanism similar to the CDM established under Article 6 for market-based cooperation across borders, while the traditional Clean Development Mechanism (CDM) allows developed countries to buy carbon credits generated in developing nations, called Certified Emission Reductions (CERs). These mechanisms work synergistically with REDD+ to create a comprehensive carbon market ecosystem, as evidenced by the Forest Carbon Partnership Facility (FCPF) where emission reductions payments more than tripled from $53.2 million in 2023 to $164.5 million in 2024 demonstrating growing government and multilateral support for forest carbon projects.

Conclusion

Climate change constitutes a significant risk to India's forest biomass and carbon sequestration capacity. Increased temperatures changed precipitation patterns and amplified extreme weather conditions have resulted in ecosystem disturbances that affect forest development and carbon retention. Human-induced activities like deforestation, land-use changes and resource utilization further intensify these issues. Despite these difficulties, India has tremendous potential to increase carbon sequestration through sustainable forestry, agroforestry and afforestation. Advances in remote sensing, ecological modeling and carbon accounting can enhance accuracy of assessment and enable evidence-based policymaking. Conservation policy strengthening, community-based forest management and global cooperation will be important in preventing climate change effects and protecting India's forests as critical carbon sinks. Finally, an active, multi-disciplinary strategy integrating scientific studies, policy measures and grassroots community involvement will be critical in making Indian forests resilient and playing their part in global climate change mitigation strategies.

Acknowledgements

I would like to thank my chairman, Dr. K. Baranidharan, for guiding me throughout the process. I am also grateful to the Forest College and Research Institute for providing me with all the facilities I needed.

Authors' contributions

DS and KB helped choose the review topic and its outline. RR contributed ideas related to the topic and drafted the manuscript. KPR corrected my remote sensing-related points. MK helped with AI-related work. MT participated in the sequence alignment. PH, MV, VK, SB, SK and ARA helped with the overall correction of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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